

# Arp 299-A: More than “just” a prolific supernova factory

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We present partial results from our monitoring of the nuclear region of the starburst galaxy IC 694 (=Arp 299-A) at radio wavelengths, aimed at discovering recently exploded CCSNe, as well as to determine their rate of explosion, which carries crucial information on star formation rates and starburst scenarios at work.

Two epochs of eEVN observations at 5.0 GHz, taken in 2008, revealed the presence of a rich cluster of compact radio emitting sources in the central 150 pc of the nuclear starburst in Arp 299A. The large brightness temperatures observed for the compact sources indicate a non-thermal origin for the observed radio emission, implying that most, if not all, of those sources were young radio supernovae (RSNe) and supernova remnants (SNRs). More recently, contemporaneous EVN observations at 1.7 and 5.0 GHz taken in 2009 have allowed us to shed light on the compact radio emission of the parsec-scale structure in the nucleus of Arp 299-A. Namely, our EVN observations have shown that one of the compact VLBI sources, A1, previously detected at 5.0 GHz, has a flat spectrum between 1.7 and 5.0 GHz and is the brightest source at both frequencies. The morphology, radio luminosity, spectral index and ratio of radio-to-X-ray emission of the A1-A5 region allowed us to identify A1-A5 with long-sought AGN in Arp 299-A. This finding may suggest that both starburst and AGN are frequently associated phenomena in mergers. Finally, we also note that component A0, identified as a young RSN, exploded at the mere distance of two parsecs from the putative AGN in Arp 299-A, which makes this supernova one of the closest to a central supermassive black hole ever detected.

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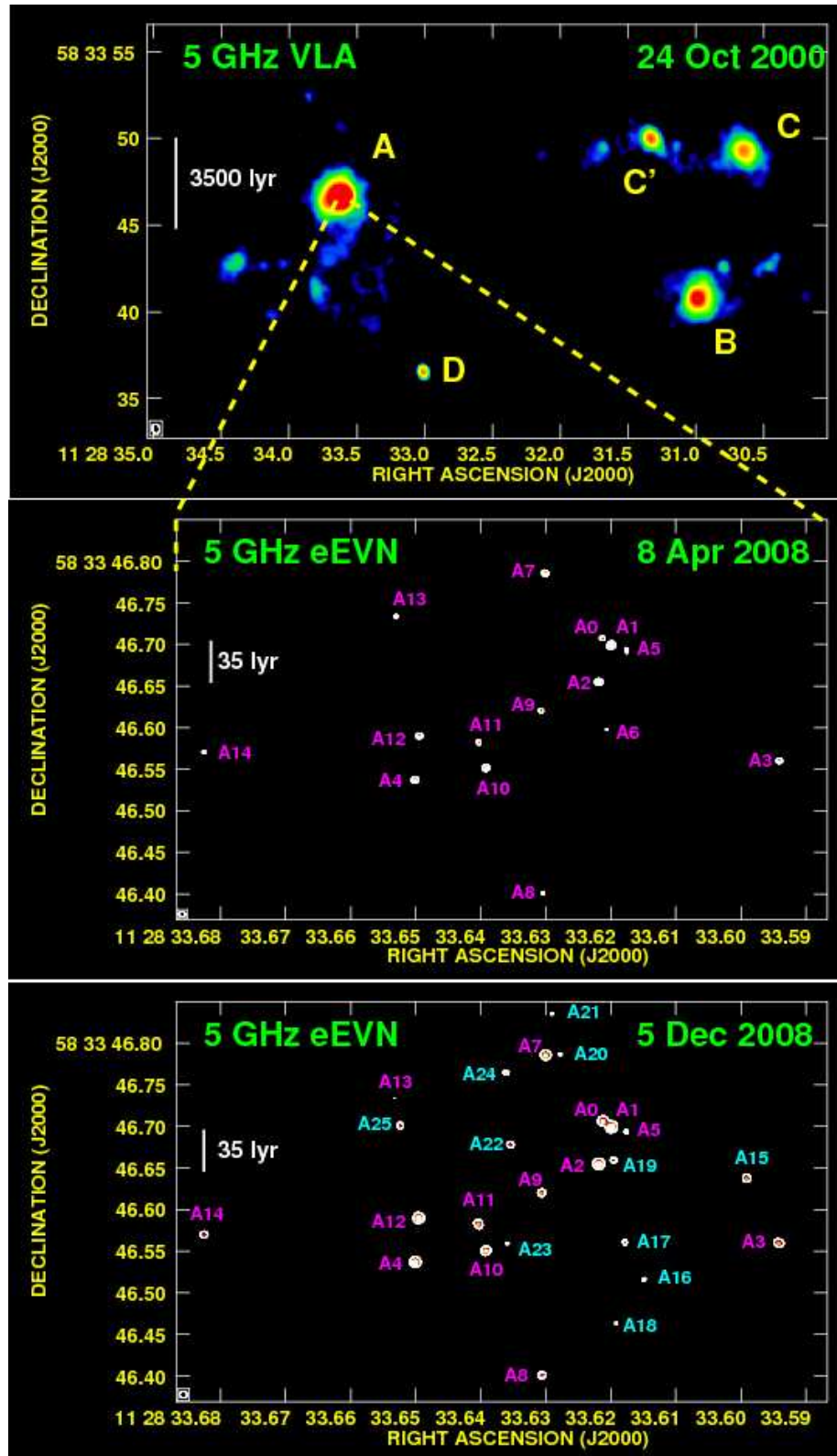
## 1. The need for high-angular resolution in LIRG studies

A large fraction of the massive star-formation at both low- and high- $z$  has taken place in (U)LIRGs. Thus, their implied high star-formation rates (SFRs) are expected to result in CCSN rates a couple of orders of magnitude higher than in normal galaxies. Therefore, a powerful tracer for starburst activity in (U)LIRGs is the detection of CCSNe, since the SFR is directly related to the CCSN rate. However, most SNe occurring in ULIRGs are optically obscured by large amounts of dust in their nuclear starburst environments, and have therefore remained undiscovered by (optical) SN searches. Fortunately, it is possible to discover these CCSNe through high-resolution radio observations, as radio emission is free from extinction effects. Furthermore, CCSNe are expected, as opposed to thermonuclear SNe, to become strong radio emitters when the SN ejecta interact with the circumstellar medium (CSM) that was ejected by the progenitor star before its explosion as a supernova. Therefore, if (U)LIRGs are starburst-dominated, bright radio SNe are expected to occur and, given its compactness and characteristic radio behaviour, can be pinpointed with high-angular resolution, high-sensitivity radio observations (e.g., SN 2000ft in NGC 7469 [10]; SN 2004ip in IRAS 18293-3413, [11]; SN 2008cs in IRAS 17138-1017, [12], [13]; supernovae in Arp 299 [14, 16, 15, 17], Arp 220 [18, 19, 20], Mrk 273 [21]). However, since (U)LIRGs are likely to have an AGN contribution, it is mandatory the use of high-sensitivity, high-resolution radio observations to disentangle the nuclear and stellar (mainly from young SNe) contributions to the radio emission, thus probing the mechanisms responsible for the heating of the dust in their (circum-)nuclear regions.

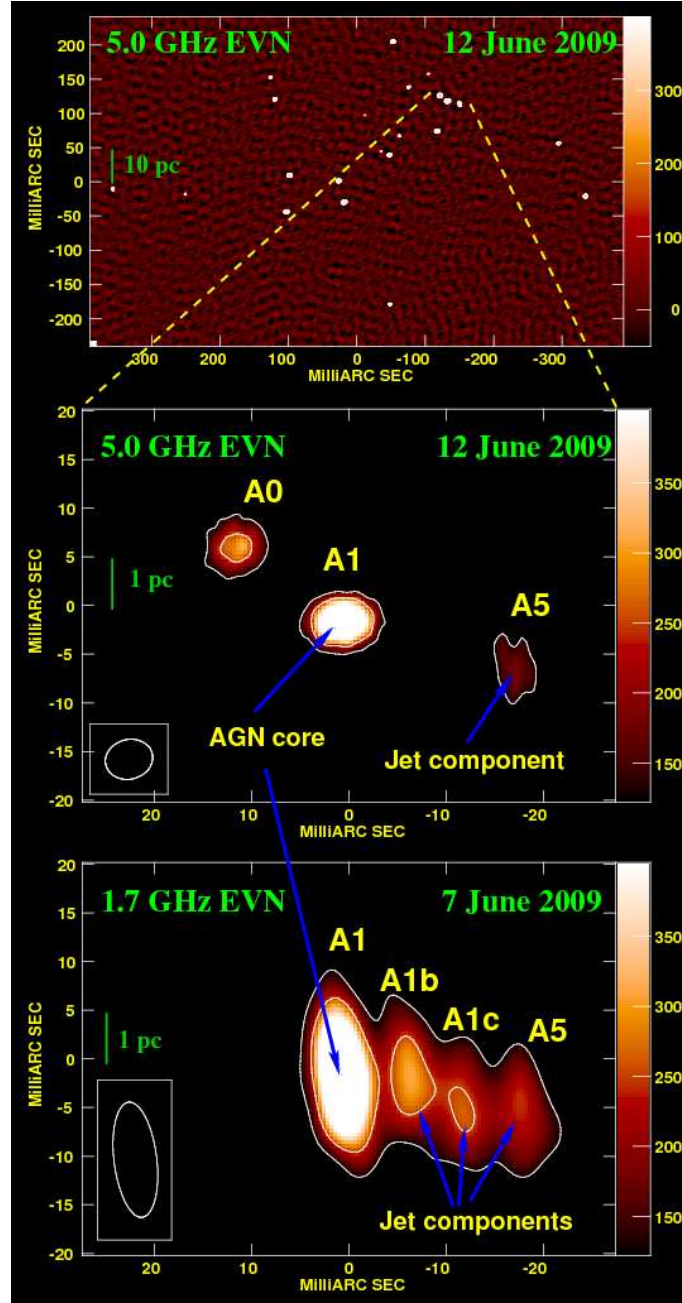
## 2. e-EVN imaging of Arp 299-A

Arp 299 (the merging system formed by IC 694 and NGC 3690) is the “original” starburst galaxy (Gehrz et al. 1983) and an obvious merger system that has been studied extensively at many wavelengths. An active starburst in Arp 299 is indicated by the high frequency of recent optically discovered supernovae in the outer regions of the galaxy. Since the far infrared luminosity of Arp 299 is  $L_{IR} \approx 6.5 \times 10^{11} L_{\odot}$ , the implied CCSN rate is of  $\approx 1.7$  SN/yr. Given that 50% of its total infrared emission comes from source A (see Fig. 1), it is expected that roughly 1 SN/yr will explode in region A. Therefore, this region is the one that shows most promises for finding new supernovae. Indeed, Neff et al. (2004) found a new component in this region, by comparing VLBA observations carried out in April 2002 and February 2003.

We proposed e-EVN observations aimed at detecting the radio emission from recently exploded SNe in Arp 299. Our observations, carried out in April 2008 and December 2008 at 5.0 GHz, resulted in the deepest images ever of Arp 299-A (see Figure 1). We found 26 compact components above  $5\sigma$  rms noise, whose nature can be only explained if they are SNe and/or SNRs, likely embedded in super star clusters, and may challenge the standard scenario that directly links far-infrared luminosity to a CCSN and star formation rate, since the apparent rate of CCSNe might be much higher than expected. We leave, however, a detail discussion of this and other issues for future publications.



**Figure 1:** *Top panel:* 5 GHz VLA archival observations of Arp 299 on 24 October 2000, displaying the five brightest knots of radio emission in this merging galaxy. *Middle and bottom panels:* 5 GHz e-EVN observations of the central 500 light years of Arp 299-A on 8 April 2008 and 5 December 2008. The off-source root-mean-square (r.m.s.) noise level is  $39 \mu\text{Jy/beam}$  and  $25 \mu\text{Jy/beam}$  for the middle and bottom panels, respectively, and show the existence of 15 and 26 compact components with a signal-to-noise ratio (s.n.r.) equal or larger than five on 8 April 2008 and 5 December 2008, respectively. The size of the FWHM synthesized interferometric beam was of  $(0.6 \text{ arcsec} \times 0.4 \text{ arcsec})$  for the VLA observations, and of  $(7.3$



**Figure 2:** *Top:* 5.0 GHz full EVN image of the central 150 parsec region of the luminous infrared galaxy Arp 299-A (=IC 694), displaying a large number of bright, compact, nonthermal emitting sources, mostly identified with young RSNe and SNRs. The image center is at RA 11:28:33.63686 and DEC 58:33:46.5806. *Middle and bottom:* Blow-ups of the inner 8 parsec of the nuclear region of Arp 299-A, as imaged with the full EVN at 1.7 and 5.0 GHz. The image center is at RA 11:28:33.61984 and DEC 58:33:46.7006 in both panels. The morphology, spectral index and luminosity of the A1-A5 region are very suggestive of a core-jet structure. The color scale goes from  $-50 \mu\text{Jy/b}$  up to  $400 \mu\text{Jy/b}$  in the top panel and from  $125 \mu\text{Jy/b}$  to  $400 \mu\text{Jy/b}$  in the middle and bottom panels. Contours are drawn at 5 and 10 times the off-source r.m.s. noise.

### 3. Summary and discussion

VLBI observations of nearby CCSNe have allowed for a better understanding of the physics, namely the determination of the deceleration parameter, interaction between ejecta and presupernova wind, characterization of the mass loss history and –sometimes– the explosion scenario, estimation of magnetic field and energy budget in fields and particles. However, this wealth of information has been obtained only for those supernovae that are bright ( $L_{\text{peak}} \gtrsim 1.5 \times 10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1}$ ), long-lasting (radio lifetimes of a few years at least) and close enough ( $D < 20 \text{ Mpc}$ ), so that VLBI observations can adequately resolve and monitor their expansion. If we consider that normal galaxies have small CCSN rates ( $\lesssim 0.01 \text{ SN/yr}$ ), and that most CCSNe (Type IIP and Type IIb) have radio peaks of a few times  $10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1}$  at most, this explains why so few radio supernovae have been observed with VLBI in the last 20 yrs, despite the VLBI arrays increasing their sensitivity. One important way in which e-VLBI may contribute significantly in this field is in the prompt response that it offers. For example, Type Ib/c SNe, recently linked to long GRBs, are known to be rapidly evolving ( $t_{\text{peak}} \approx 10 - 20 \text{ days}$ ) radio supernovae. Currently VLBI arrays do not offer the needed dynamic scheduling to, e.g., react on a nearby event, while e-VLBI offers such flexibility and, thanks to its ability to carry out real-time correlation, allows for a potential follow-up of the most interesting targets.

The CCSN rate in (U)LIRGs is expected to be at least one or two orders of magnitude larger than in normal galaxies [23], and hence detections of SNe in (U)LIRGs offer a promising way of determining the current star formation rate in nearby galaxies. However, the direct detection of CCSNe in the extreme ambient densities of the central few hundred pc of (U)LIRGs is extremely difficult, as the optical and IR emission of supernovae is severely hampered by the huge amounts of dust present in those regions, and can at best yield an upper limit to the true CCSN rate. Fortunately, it is possible to directly probe the star forming activity in the innermost regions of (U)LIRGs by means of high angular resolution, high-sensitivity radio searches of CCSNe, as radio does not suffer from dust obscuration. Current VLBI (and e-VLBI) arrays are starting to yield astonishing results, thanks to their few- $\mu\text{Jy}$  sensitivity and milliarcsec resolution at cm-wavelengths. In particular, the findings in Arp 220 using global VLBI and Arp 299 (using the e-EVN), may challenge the standard scenario that directly links far-infrared luminosity to a CCSN and star formation rate, which is of much relevance for studies of starburst galaxies at high- $z$ .

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